Continental shelf-ocean exchange

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With considerable help from John Huthnance (National Oceanography Centre
UK) and Jose Blanco (Chile)

“The objective of the Coastal Interim Synthesis Activity is to stimulate the synthesis of observational and modeling results on carbon cycle fluxes and processes along the North American continental margins”

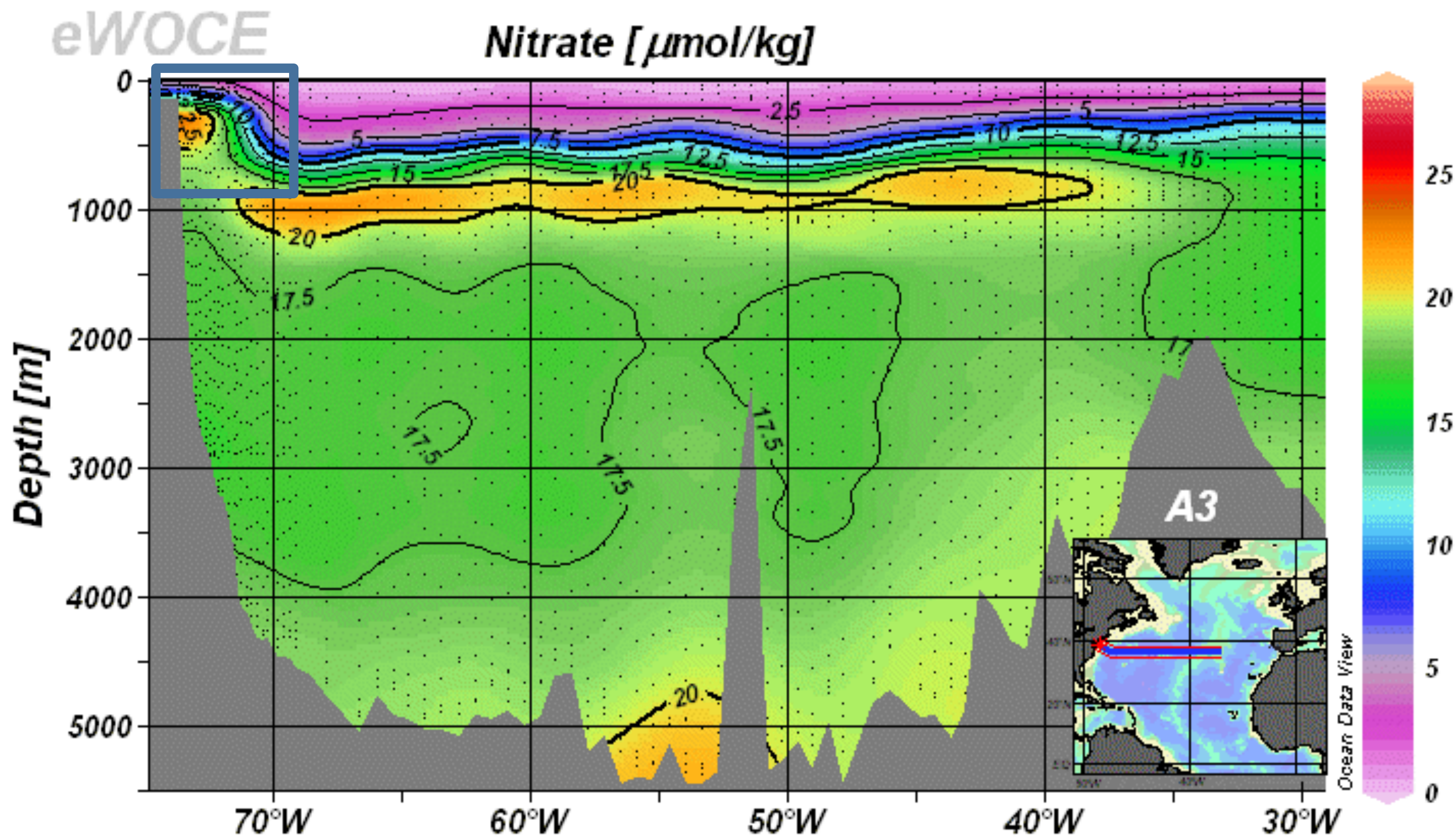
- My goal – to make sure you keep in mind the diverse processes at work in the coastal ocean and their relation to the carbon cycle.

- Much of this comes from our paper in The Seas and a 1995 paper by Huthnance. And KK Liu et al recent book.

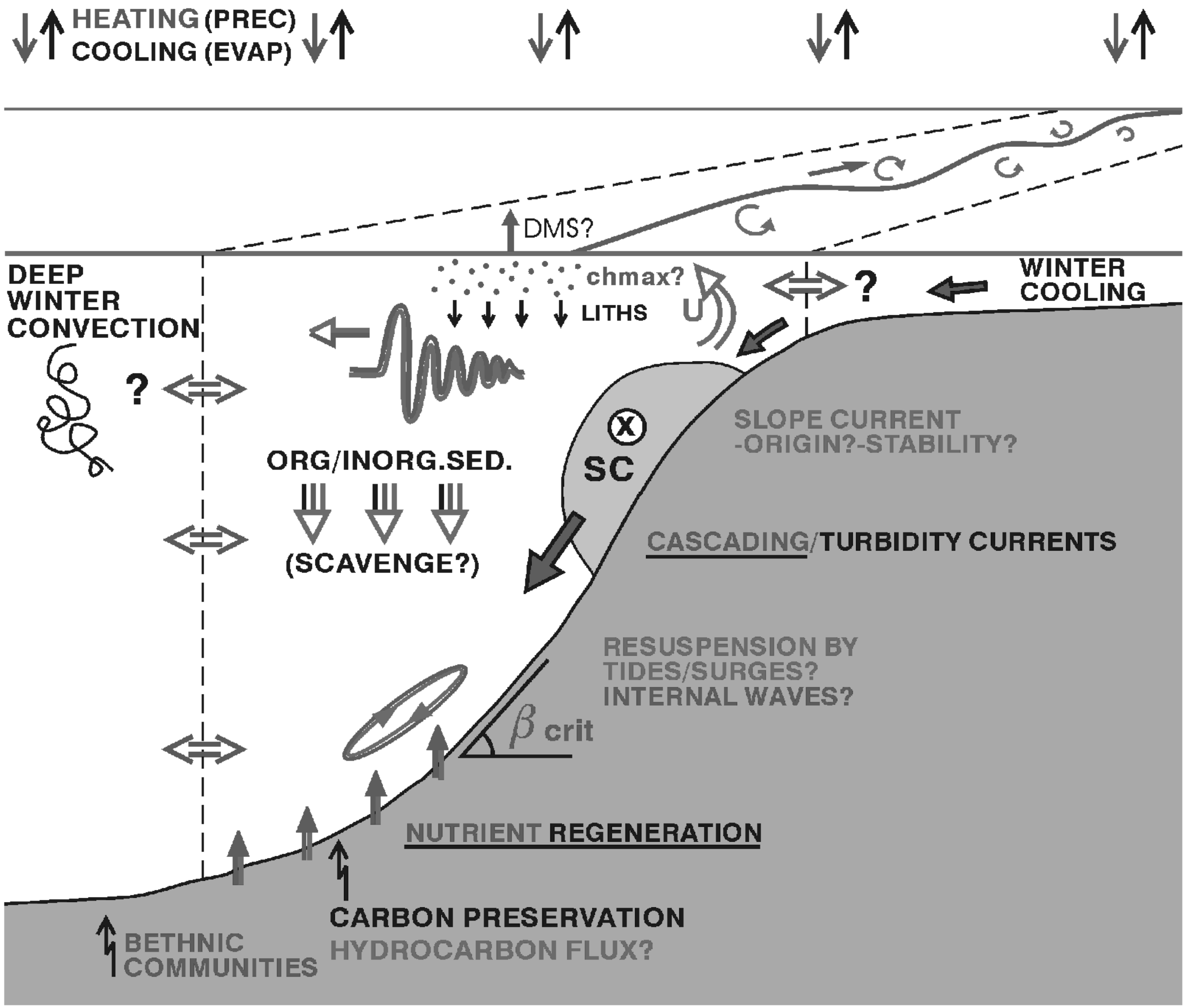
Outline

- Some historical perspective
- The Processes
  - River plumes
  - Along-slope Currents
  - Cross-shelf transports
  - Mixing Processes
- Regional Look
  - East Coast –SAB and MAB
  - Gulf of Mexico
  - West Coast and Alaska

The issue – a small 'twitch' at the edge can have huge impact on the ocean margin processes. What are the 'twitches'



A quick look at processes



Alfred Redfield

- "…fertility of the sea depends upon the restoration to the surface of plant nutrients such as phosphates and nitrates liberated by the decomposition of organic matter within its depths.
- In shallow coastal waters the turbulence due to wind and tide, aided in high latitudes by the instability resulting from cooling in winter, suffice to maintain this part of the nutritional cycle. In the deep sea, organic matter generated in the surface as the result of photosynthesis processes appears in large part to sink to great depths before being finally oxidized to its ultimate inorganic products."

http://www.whoi.edu/page.do?pid=10897&i=4621&x=141

" … four processes by which these materials are brought again to the surface in the Atlantic Ocean and thus made available for the organic cycle … [Include] …

(1) upwelling resulting from offshore trade winds off the African coast;

(2) upwelling of deep Atlantic water in the Antarctic;

(3) upwelling in the boundary between currents as in the Arctic polar front; and

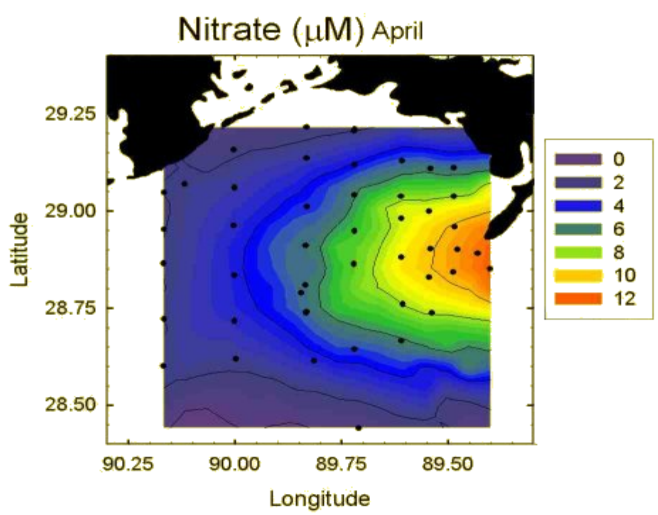
(4) winter convection in high latitudes."

Gordon Riley

- "Mathematical model of nutrient conditions in coastal waters" 1967
- The importance of the deep-water source of nutrients to coastal waters:
- "Coastal waters generally are more productive than the open sea. Two factors are believed to be responsible, in varying degrees according to local circumstances. The first is **shoreward transport**, from the edge of the continental shelf, of deep and nutrient rich water, which then becomes available to surface phytoplankton populations in the inshore waters as a result of tidal vertical mixing. The other is enrichment by **freshwater drainage**."
- He further noted that:
- "**General conclusions are that the usual pattern of exchange between inshore and offshore waters tends to enrich the coastal zone irrespective of enrichment by freshwater drainage…"**

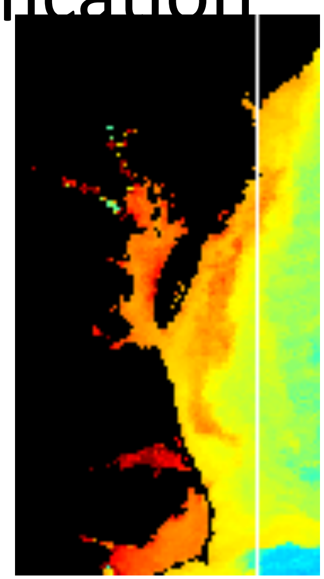
Riverine Input – where plumes go

- Highly variable
- Depends on path to ocean: Chesapeake vs Mississippi
- Small compared to Ocean source
- But comes with buoyancy = stratification

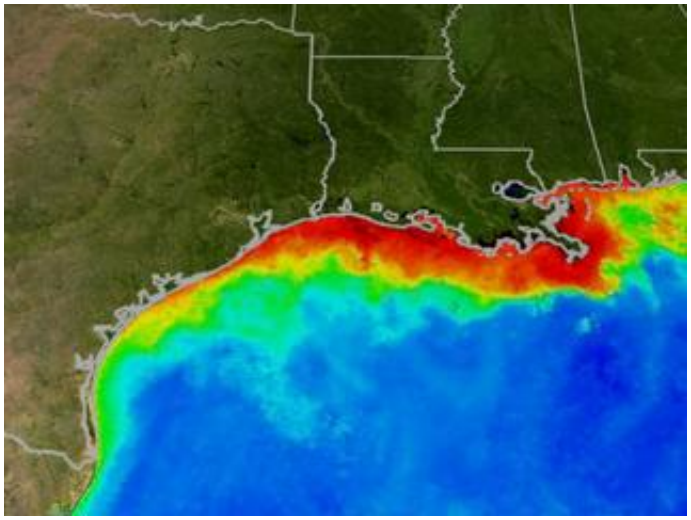


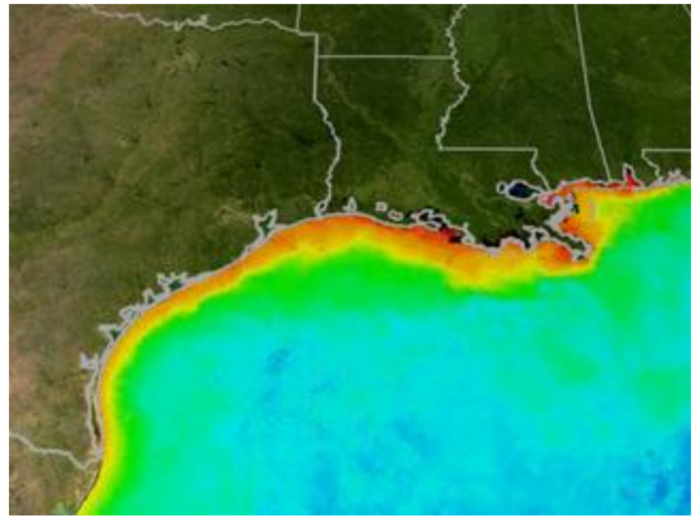
←-Mississippi

Chesapeake Bay -→



Mississippi River
Summer and Winter

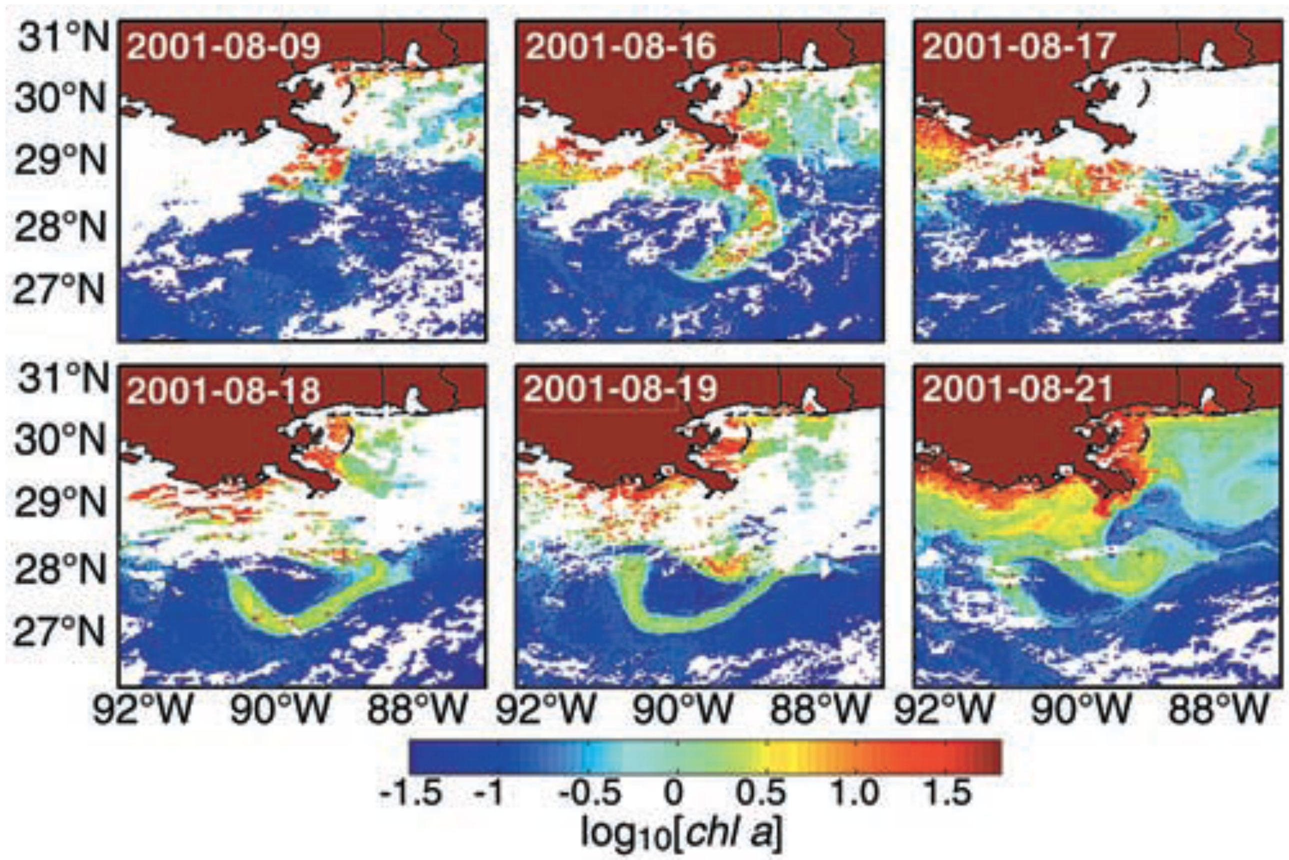




Chlorophyll maps show area of influence, coastal currents, offshore advection.

What is the comparative effect of stratification because of buoyancy flux vs the nutrient influx from the river?

Storm-induced injection of the Mississippi River plume into the open Gulf of Mexico – a common ocean margin process

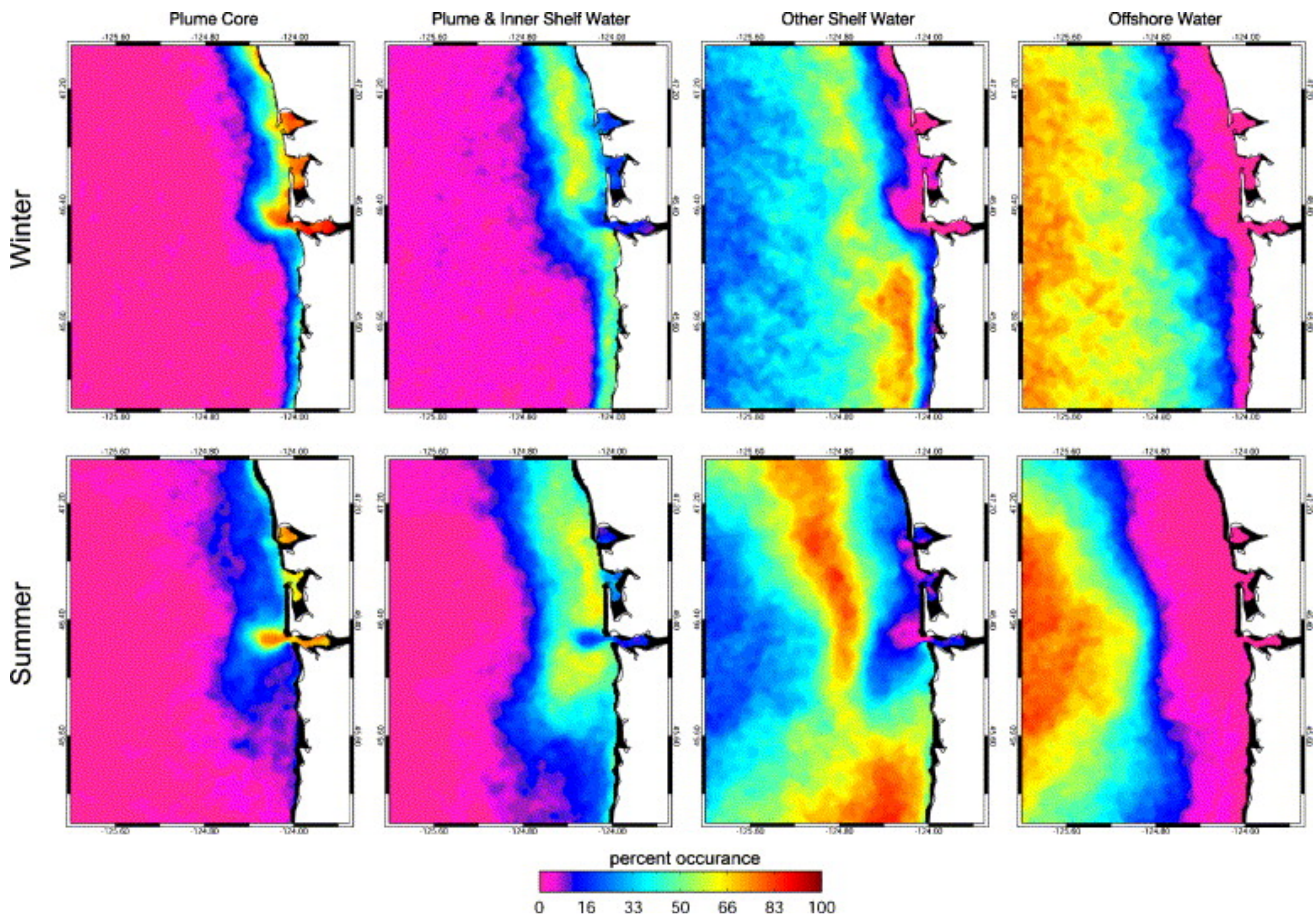


Yuan, Miller, Powell and Dagg. GEOPHYSICAL RESEARCH LETTERS, VOL. 31, 2004

Columbia River Plume – an example of plume dynamics and effect on ocean margins

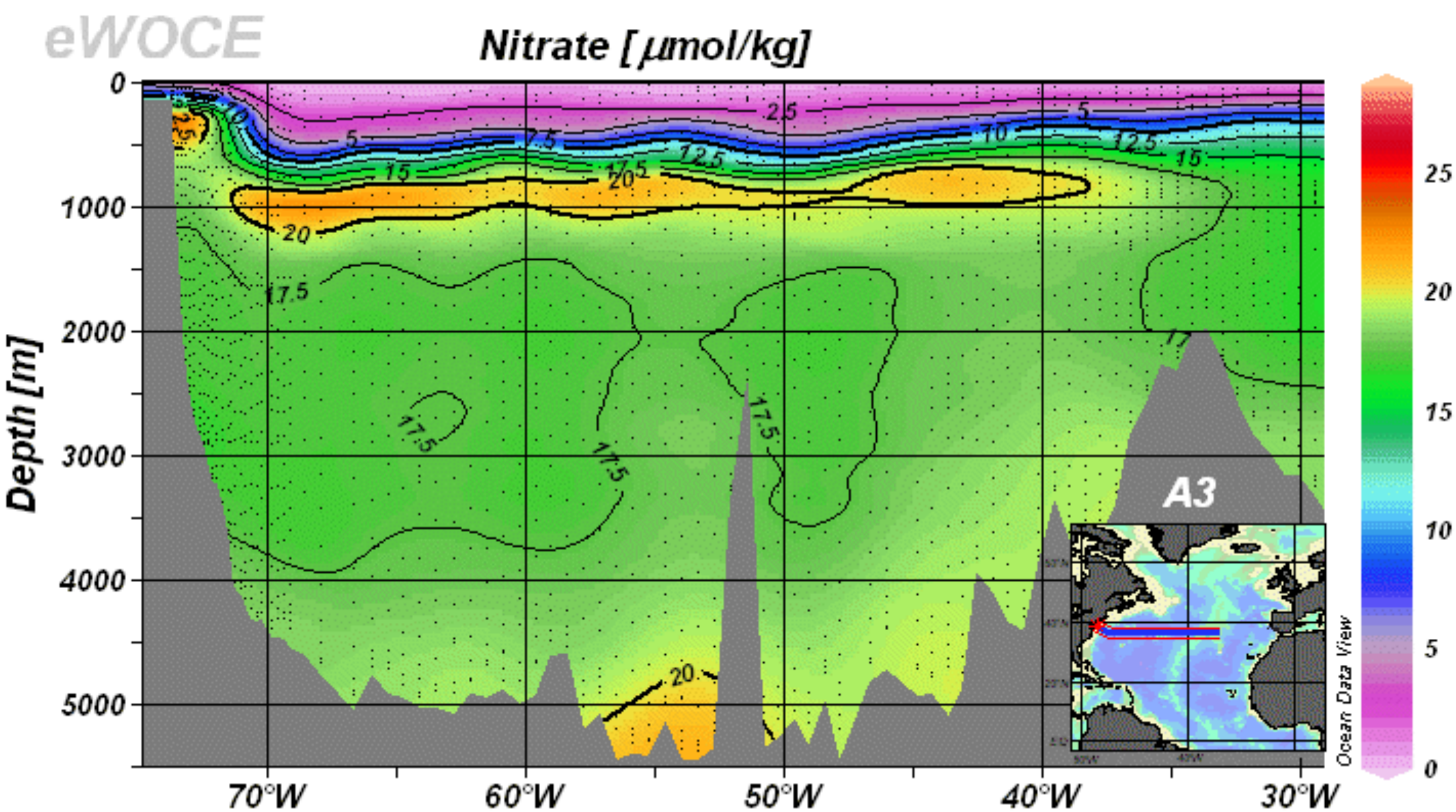
Offshore boundary

← True color of plume



Thomas and Weatherbee, **Remote Sensing of Environment**
Volume 100, Issue 2, 30 January 2006, Pages 167-178

Oceanic Inputs – What processes bring the nearly inexhaustible supply of nutrients in the deep ocean to the ocean margin and stimulate primary production?



Shelf Edge Circulation (not exchange) Processes

Processes	Speed, m/s
Coastal Current	**0.1 to 1 ←**
Slope Current Forced by -	
---JEBAR (joint effect of baroclinicity and relief)	0.1
---Steady Wind	0.1
---Unsteady Wind	0.1
---Biased form drag	0.01
---Wave Rectification	0.01
---Eddy Momentum	0.1
Western Boundary Current	**1 <-**
Eddies, warm core rings, jets	0.5
Tides	0.3
---in straits and marginal seas	>1

Shelf Edge Exchange Processes

Process	Estimated values m3/s per m coastline
Slope Currents	1
Eddy	1
Warm Core Ring Streamer	1 Sv over whole MAB
Impulsive Wind	1
Upwelling Wind	1
Western Boundary Current divergence	20
Jets in narrow shelf upwelling areas	2
Cascading	1
Front	0.3
Along isopyncal	0.2
Tides	10
Internal tide solitons	1
Wave's Stokes Drift	1

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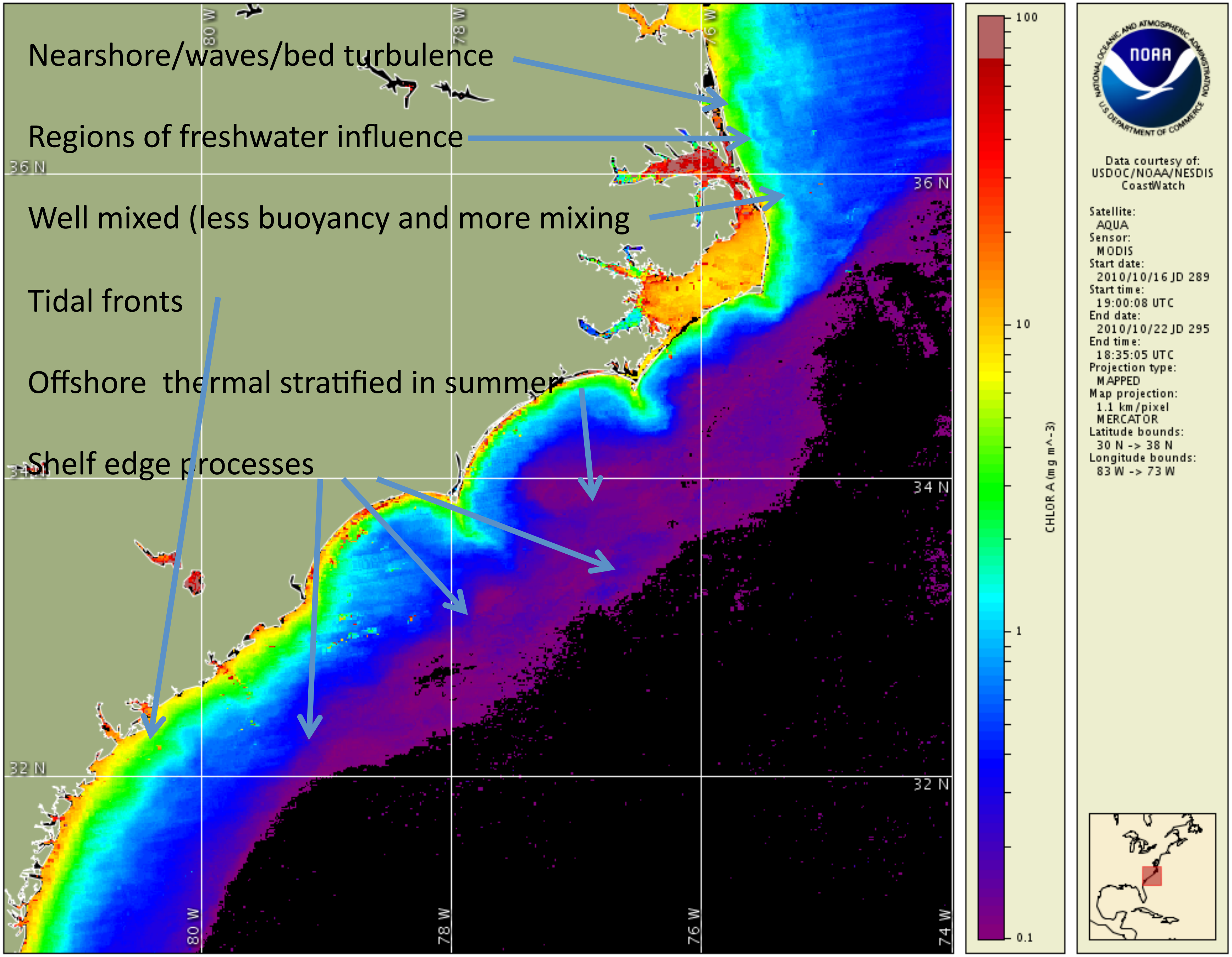

Nearshore/waves/bed turbulence
Regions of freshwater influence
Well mixed (less buoyancy and more mixing
Tidal fronts
Offshore thermal stratified in summer
Shelf edge processes
36 N
34 N
32 N
80 W
78 W
76 W
74 W
100
10
1
0.1
CHLOR A (mg m^-3)
NOAA
Data courtesy of:
USDOC/NOAA/NESDIS
CoastWatch
Satellite:
AQUA
Sensor:
MODIS
Start date:
2010/10/16 JD 289
Start time:
19:00:08 UTC
End date:
2010/10/22 JD 295
End time:
18:35:05 UTC
Projection type:
MAPPED
Map projection:
1.1 km/pixel
MERCATOR
Latitude bounds:
30 N -> 38 N
Longitude bounds:
83 W -> 73 W

Along Slope Currents

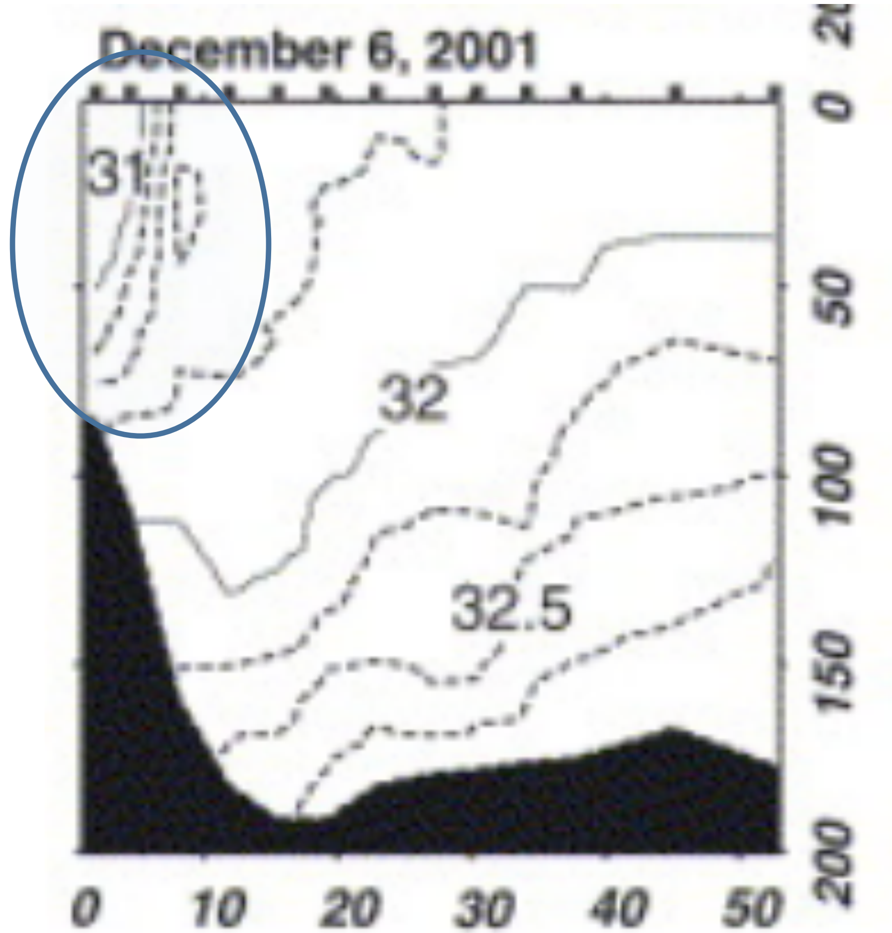
- Strong alongshore currents at the shelf break are common
- But, cross isobath flow does occur, esp in bottom Ekman layers as does vertical motion
- So along slope currents are important to nutrient supplies and carbon budgets
- Let’s look at buoyancy forced currents, western boundary currents, and eddies, warm core rings and jets.

Buoyancy forced baroclinic coastal currents

Some are over the inner
Shelf where shelves are
wide
Like off the east and Gulf
coast.
Upwelling events can move
the buoyant surface layer
offshore.
Or….

Buoyancy forced baroclinic coastal currents

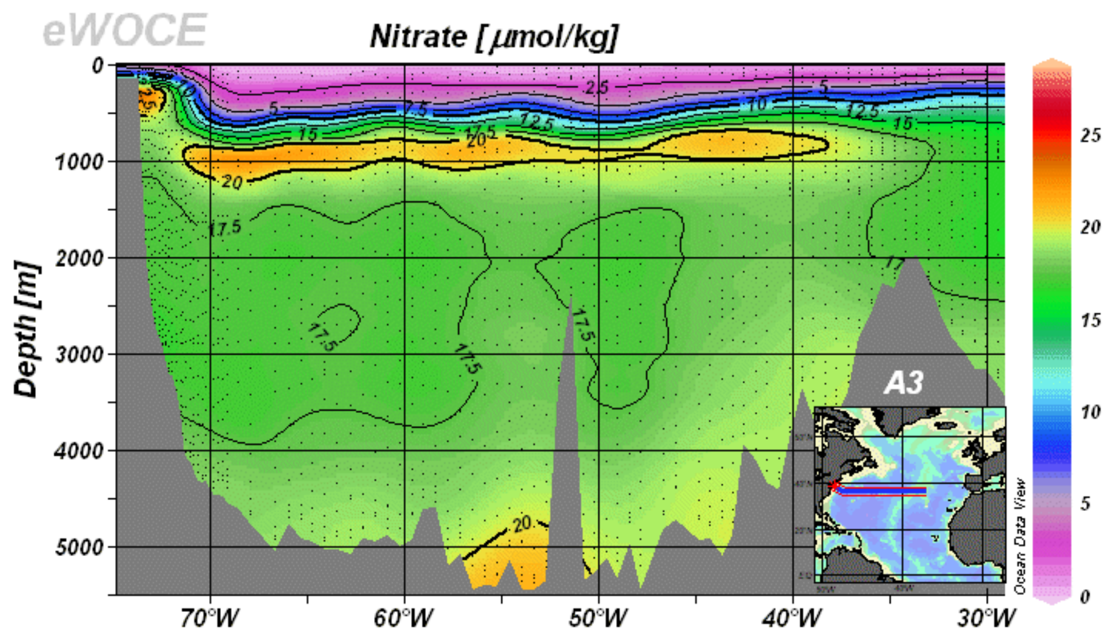
Some are over the shelf break or slope like off Alaska



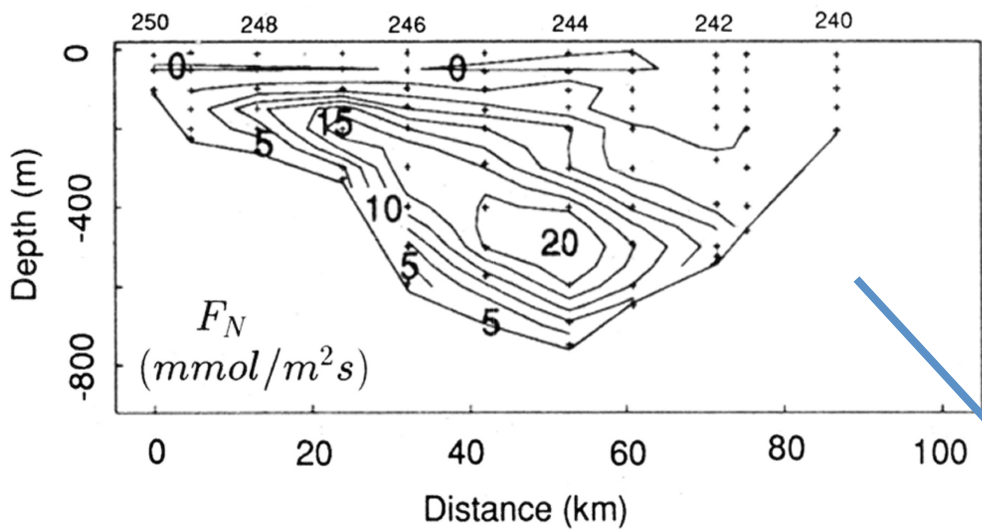
Weingartner, Danielson, and Royer, 2005, DSR

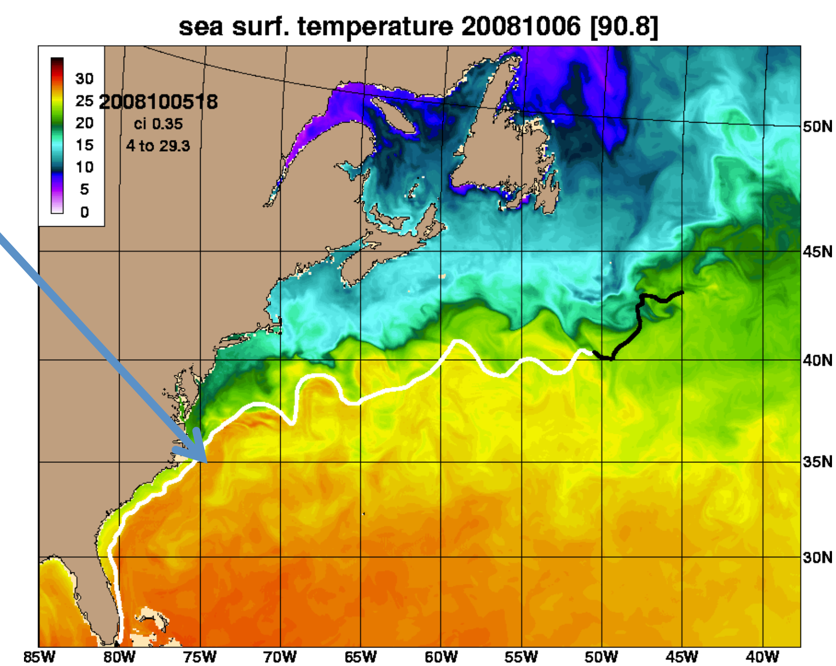
And now, Western Boundary Currents

- **Shelf parallel flow** – the ‘nutrient stream’
- Inherent dynamics – cross-slope flow along **isopyncnals and diapyncal mixing**
- **Instabilities** in the front – bathymetric interactions, Ekman related upwelling and cross-isobath flow.



***The Nutrient Stream** – poleward flux of nitrate off South Carolina – the 'Supply'*





Nutrient Transport and Mixing in the Gulf Stream

J. L. Pelegrí, G. T. Csanady, JGR VOL. 96, NO. C2, PP. 2577-2583, 1991

Iso/Dia-pycnal flow – back to some history

- I've already mentioned Redfield on this.
- Charlie Yentsch (1974)

"The combined effects of the earth's rotation and pressure gradients which are associated with ocean current flow produce the effect of drawing water in along the right side of a current …

and discharging into a counter current to the left of the main flow. …

This transfer of waters is along lines of equal density which slope dramatically upward toward the coast. The higher density waters are nutrient rich and stimulate production along the left side of the current. …

This means the biochemical factors of slope and coastal waters are generated from nutrient characteristics of deep open ocean waters."

Isopycnal and Diapycnal Flow

- Nitrate at 100m showing 'outcropping' off mid-Atlantic

Cross-isopyncal flow in Gulf Stream meanders

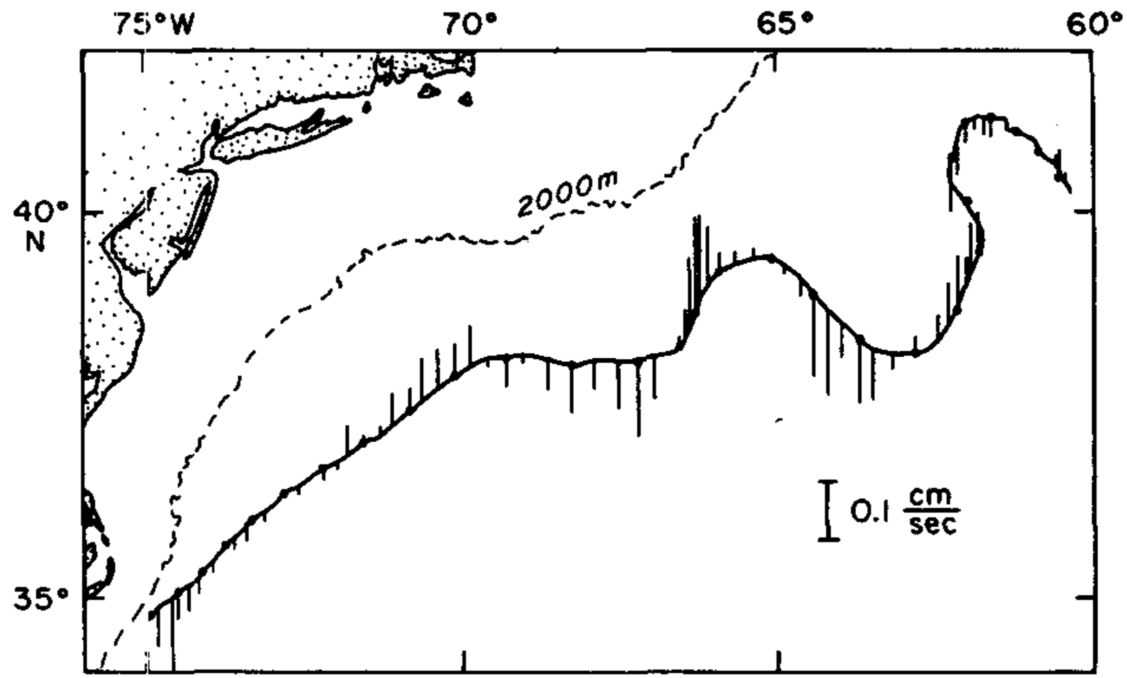
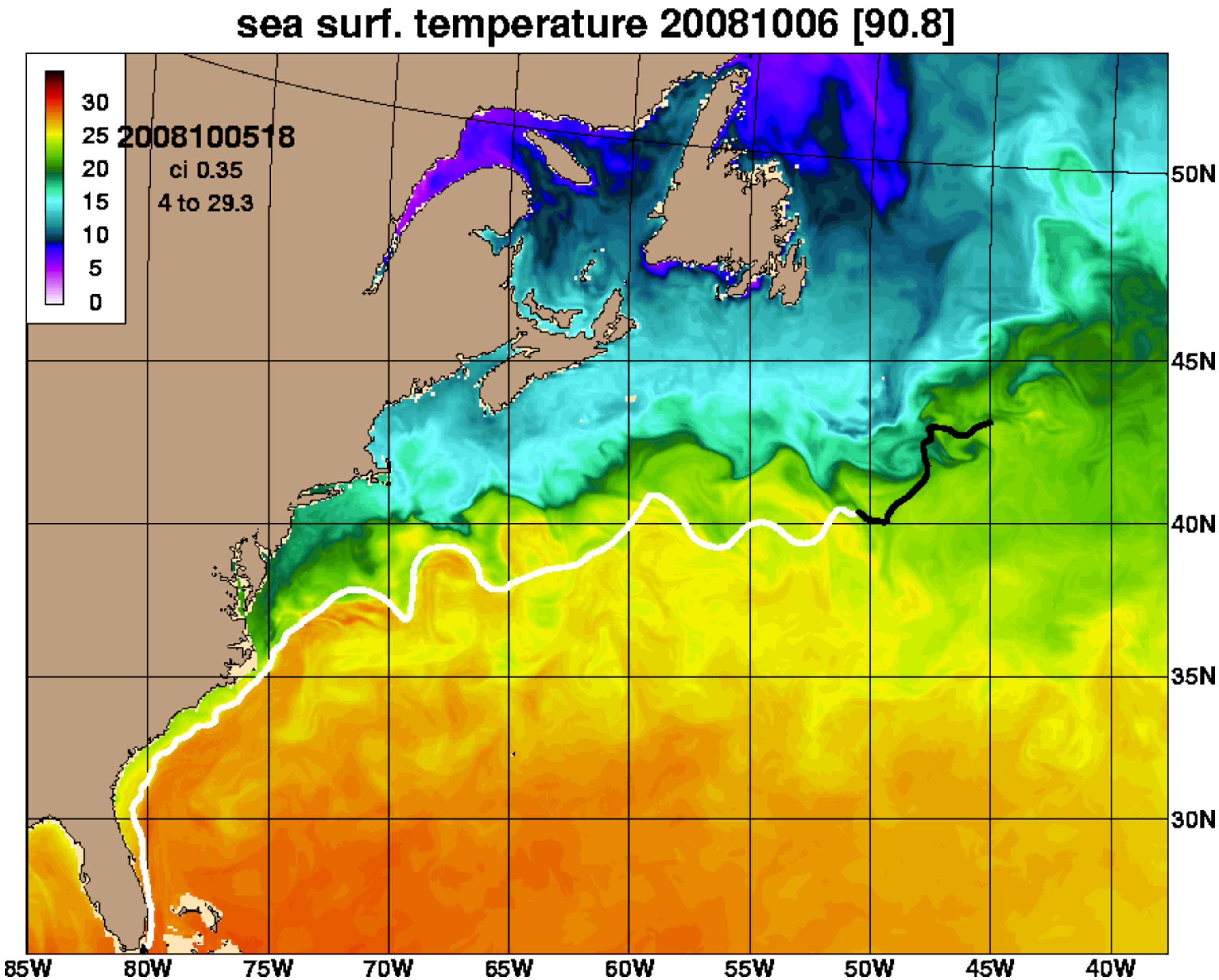


FIG. 5. RAFOS 20 (1984, 12°C) with bars indicating vertical velocity. Bars point northward for $w > 0$ and southward for $w < 0$.

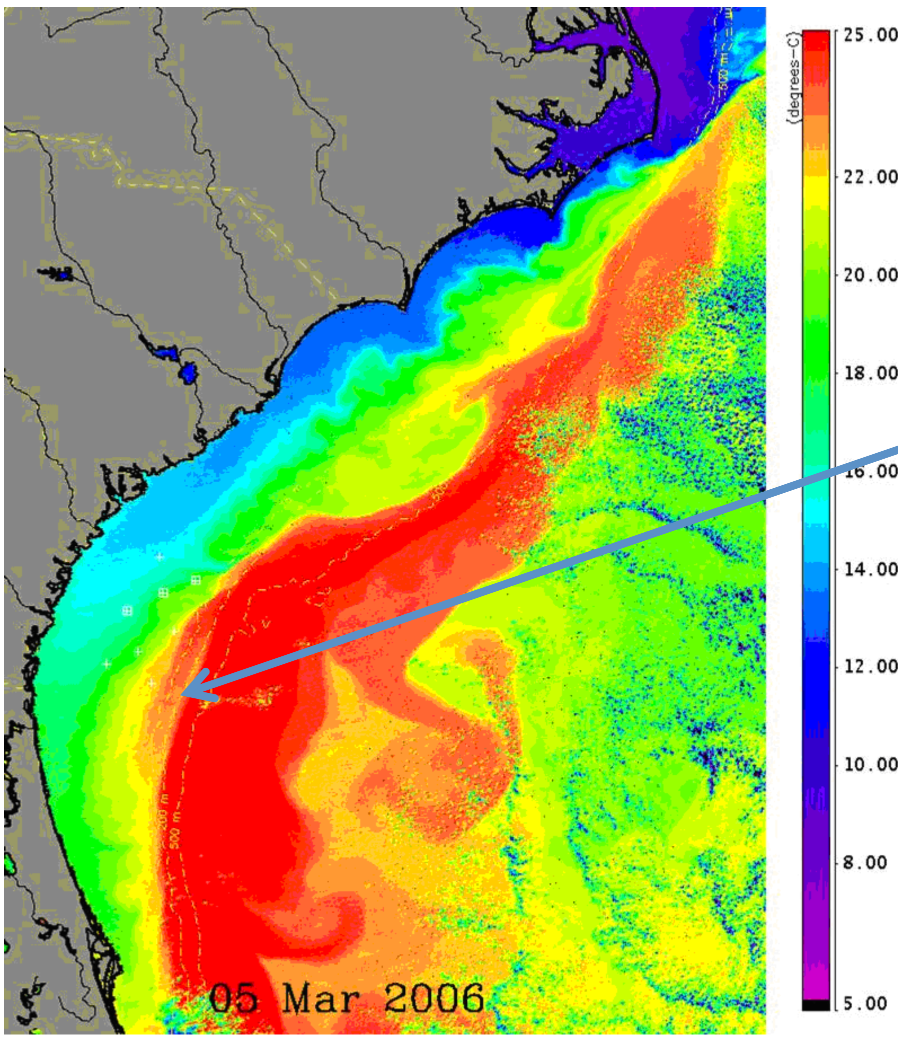
Bower and Rossby, JPO, 1989

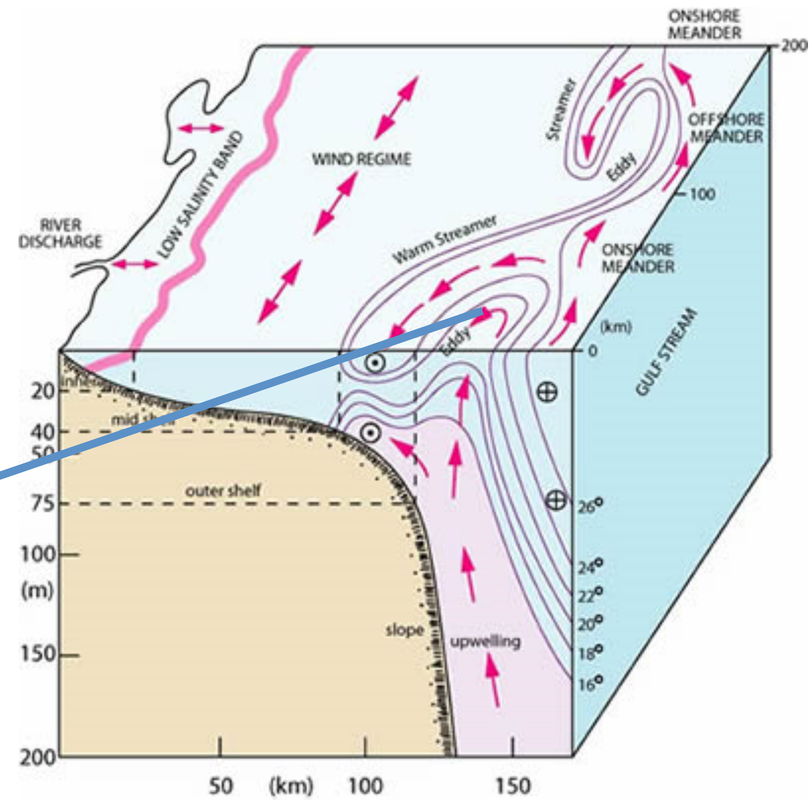
Eddies and Meanders



http://www7320.nrlssc.navy.mil/GLBhycom1-12/glfstr.html

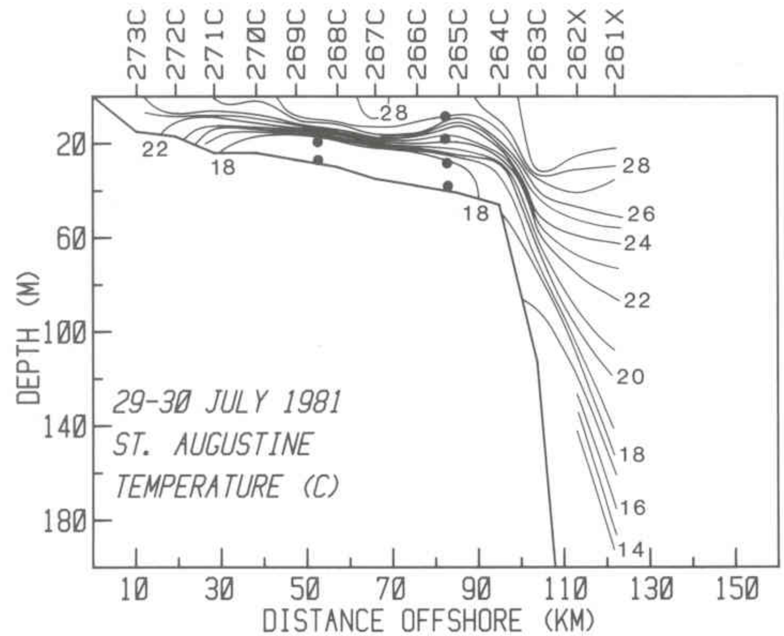
Frontal Eddies

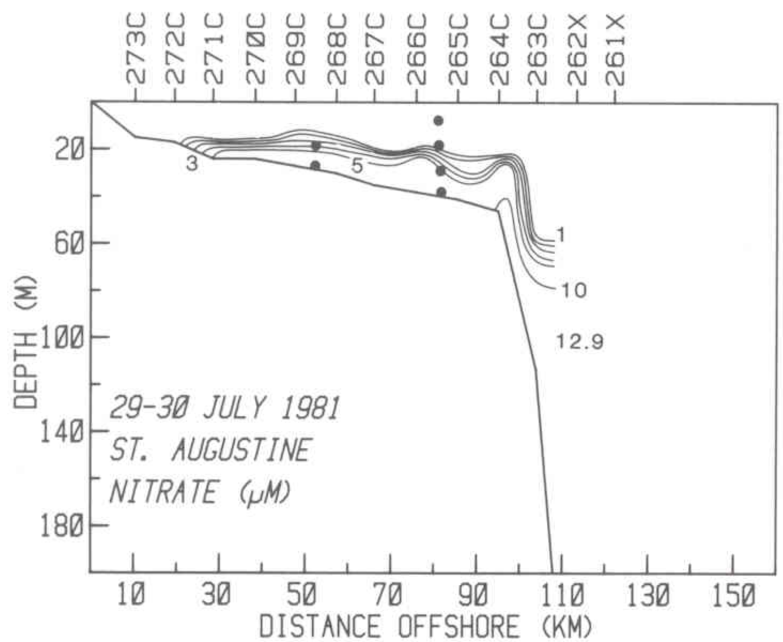




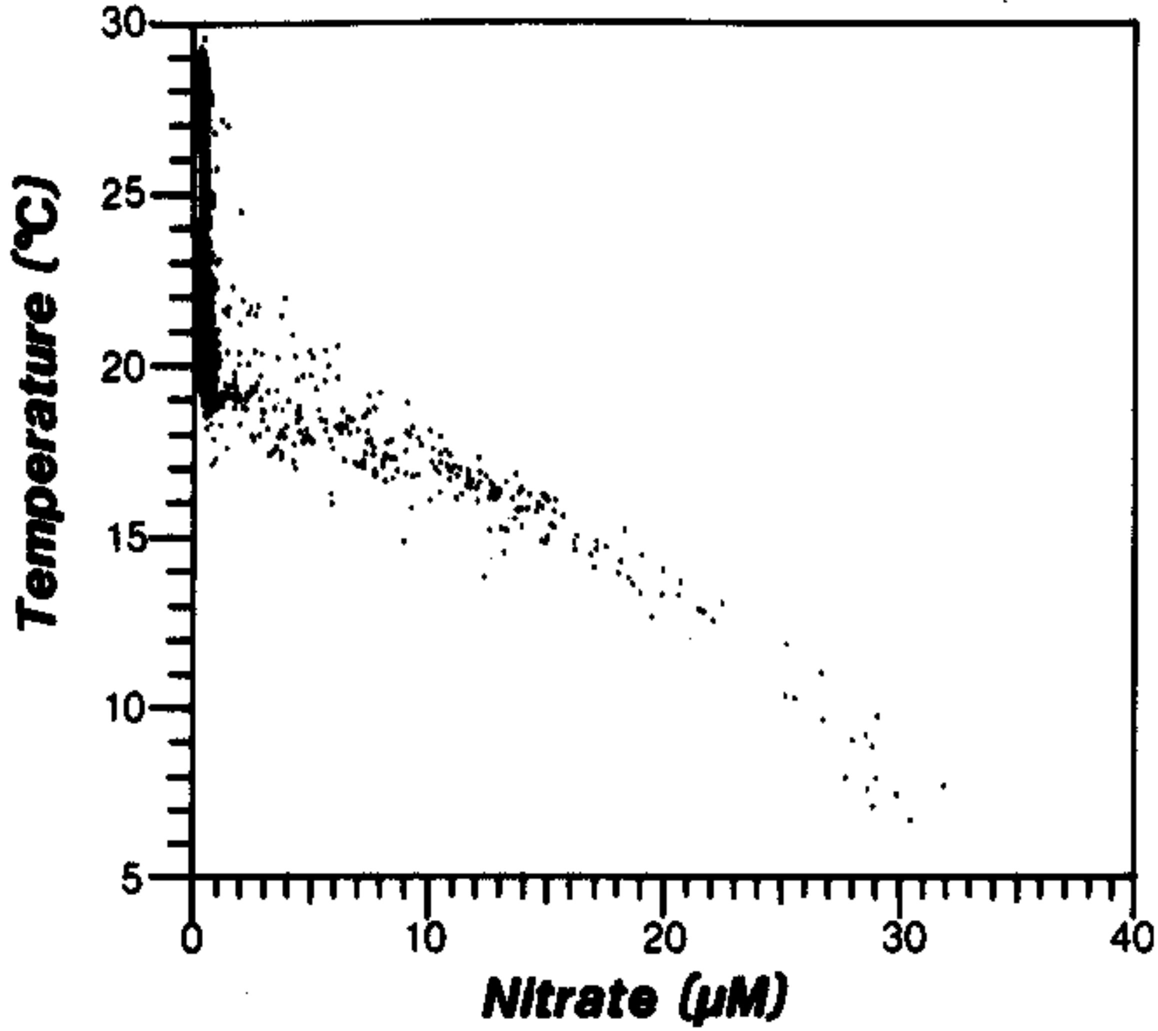
Schematic of Gulf Stream frontal eddies and meanders together with shelf flow regiems on the SAB.

Subsurface Intrusions dramatic example of cross isobath flow and PP

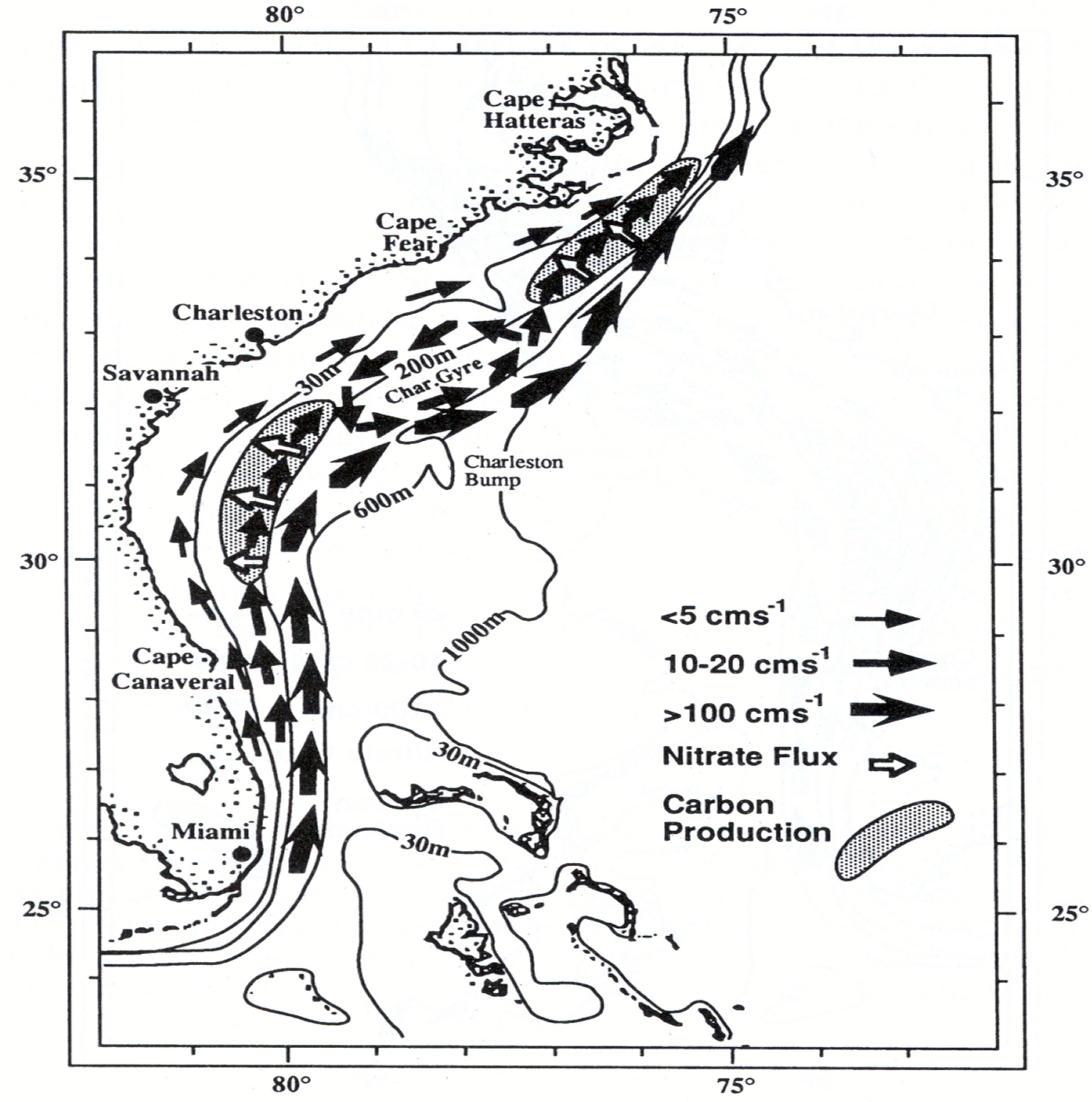




Off east coast T good proxy for nitrate.
So current measurements could lead to flux measurements



Resulting on/offshore flux and producton



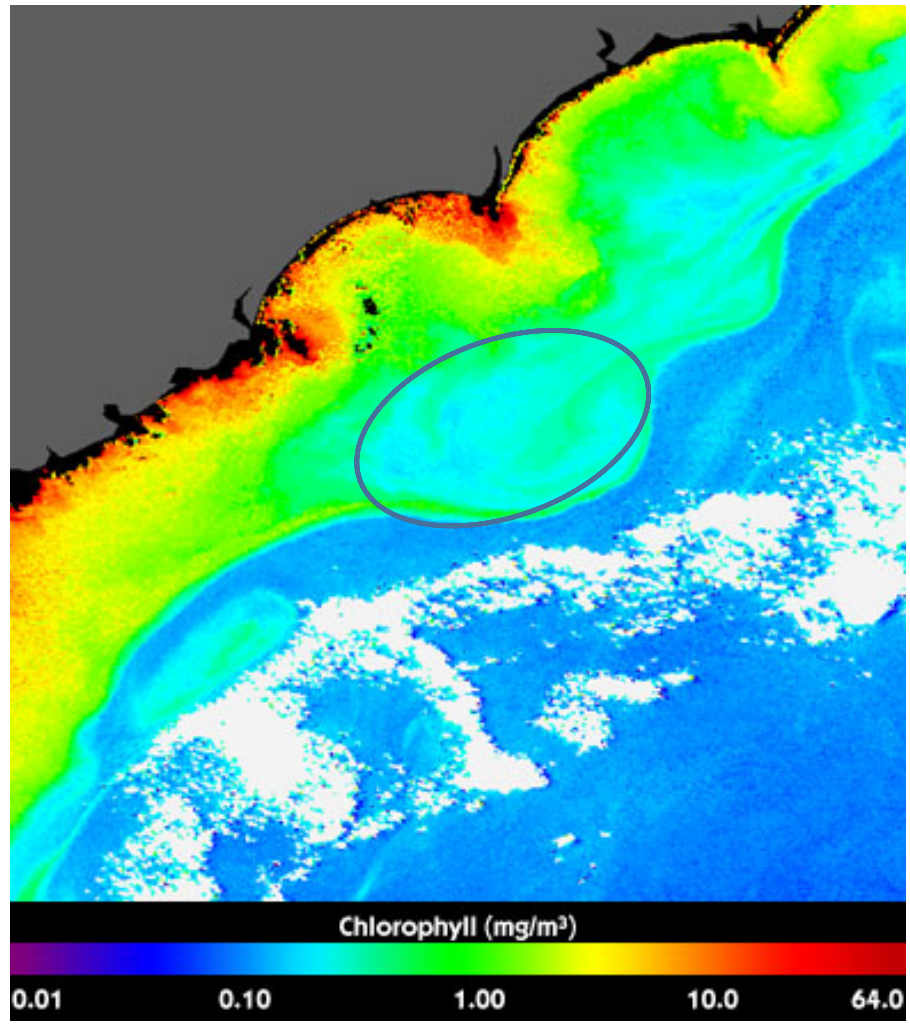
Yoder, Lee et al

Bathymetric interaction – the Charleston Bump/Gyre

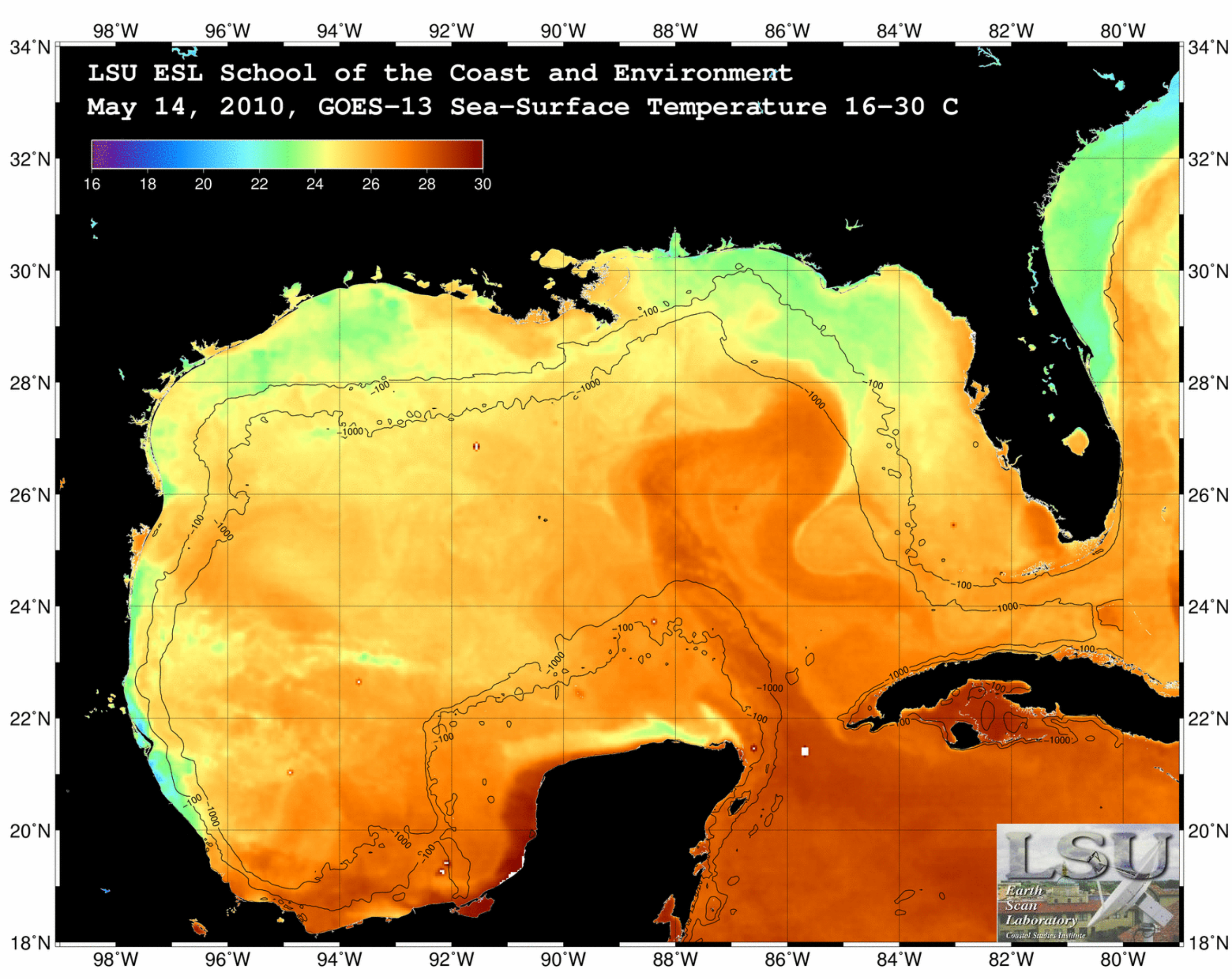
Cyclonic circulation around upwelling dome.

Moves warm surface water onshore creating stratification in the winter time.

High concentrations of salps in winter. Semi-permanent feature.



And then the Loop current (that, thanks to the oil spill, more people know about)



And now, Cross shelf flow

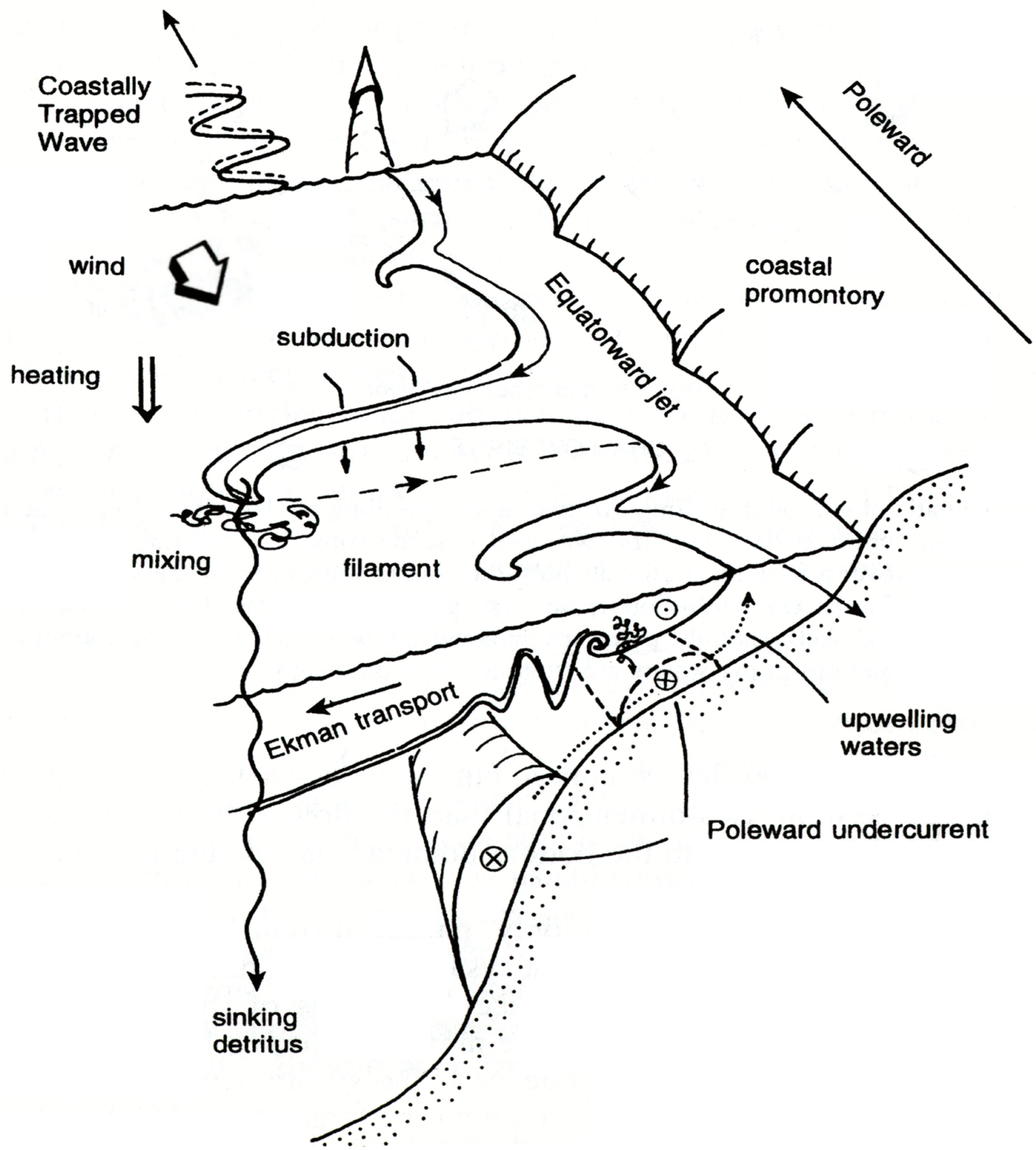
- Upwelling
- Canyons
- Capes
- Embayments
- Coastal trapped waves
- Tidal processes

Cross isobath flow processes

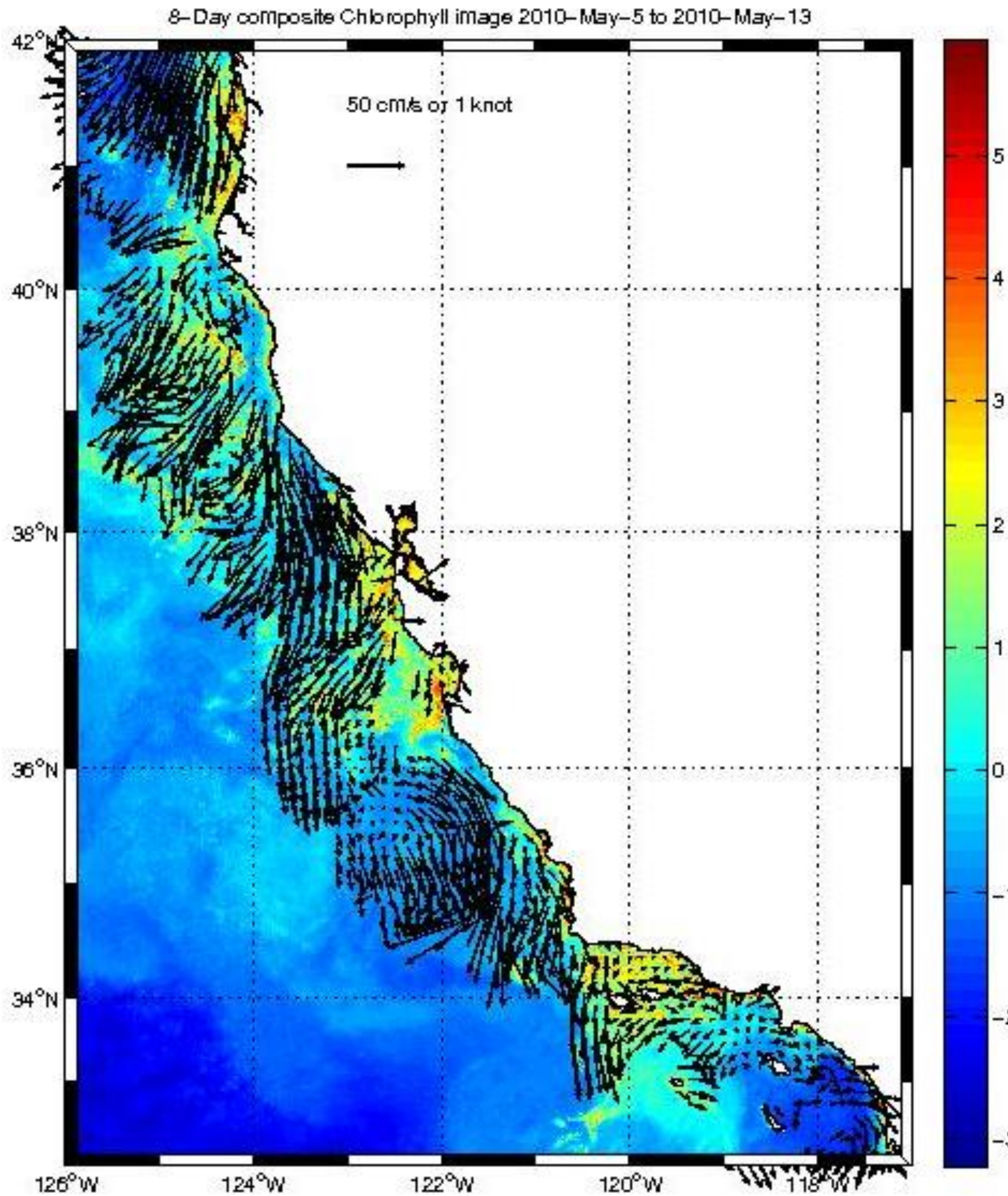
Process	m^2/s
Western boundary current and bend	0.5 Sv
Slope current and bend	0.5 Sv
Cape eddy	0.01 Sv
Canyon return flow	10
Ridge associated upwelling	1

Huthnance 1995

The schematic!



Surface chl and surface currents Note cross-slope flow and upwelling centers

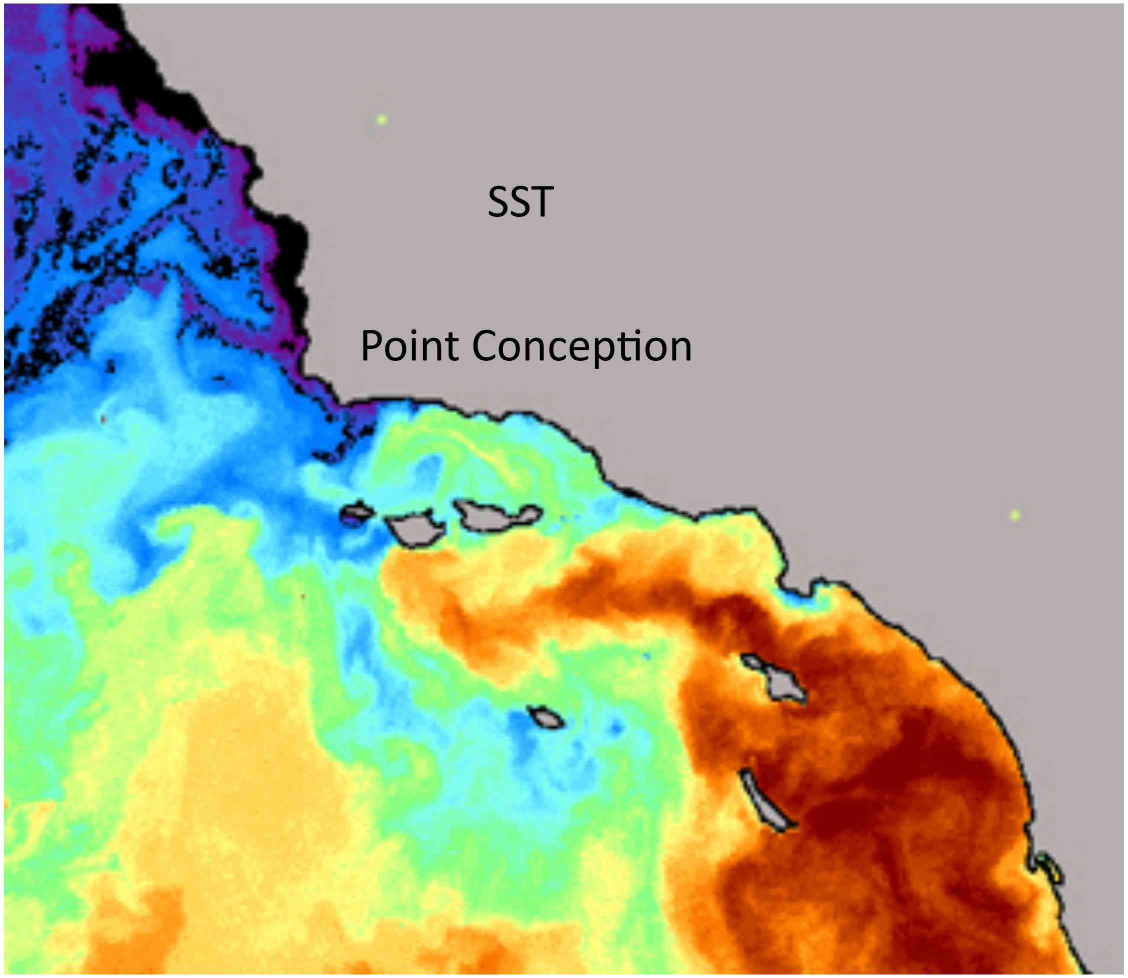


Upwelling centers, jets, filaments

Upwelling center at Pt Conception

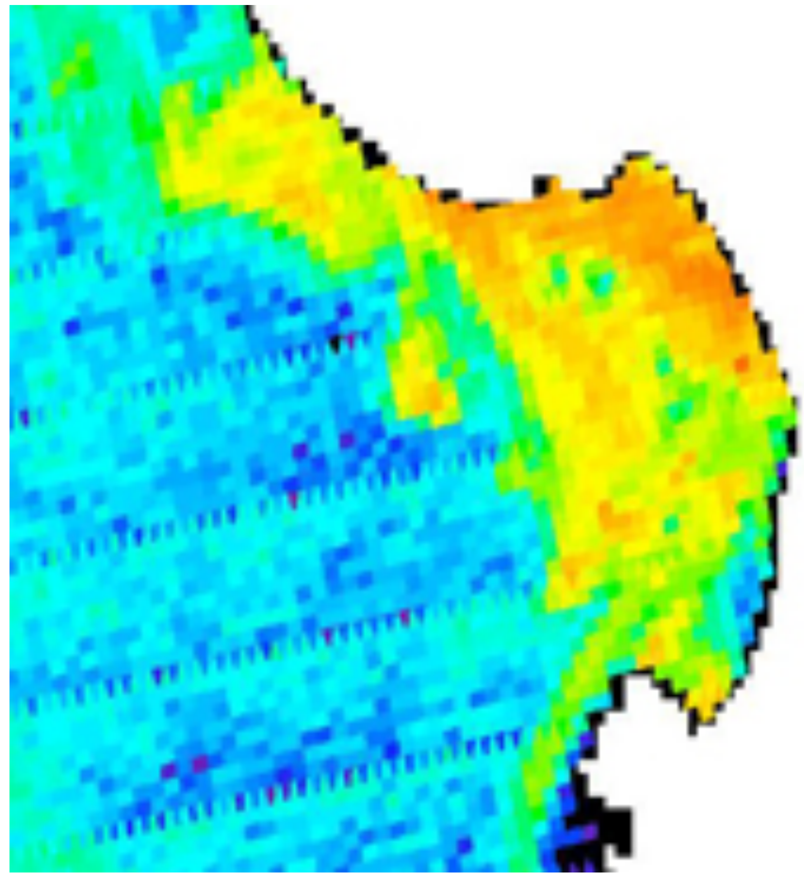
Offshore jets can be left offshore with next downwelling cycle.

Coastal waters go 100's km offshore with high production.



Embayments - recycling

Monterey
Bay
chlorophyll



Comparison of Available Mixing Energy in mW/m^2

Process	Typical Mixing Energy
Buoyancy Flux (heat, cool, rain, evap)	1
Surface Waves	150
Wind	10
Internal Tides	50
Internal Waves	10
Bottom-reflected internal waves	1
Bottom Friction – typical currents	3
Bottom Friction – tidal currents	100 to 1000
Canyon-intensified internal waves	150

Mixing Processes

Top – typical SE shelf
Bottom – resuspension after passage of hurricane

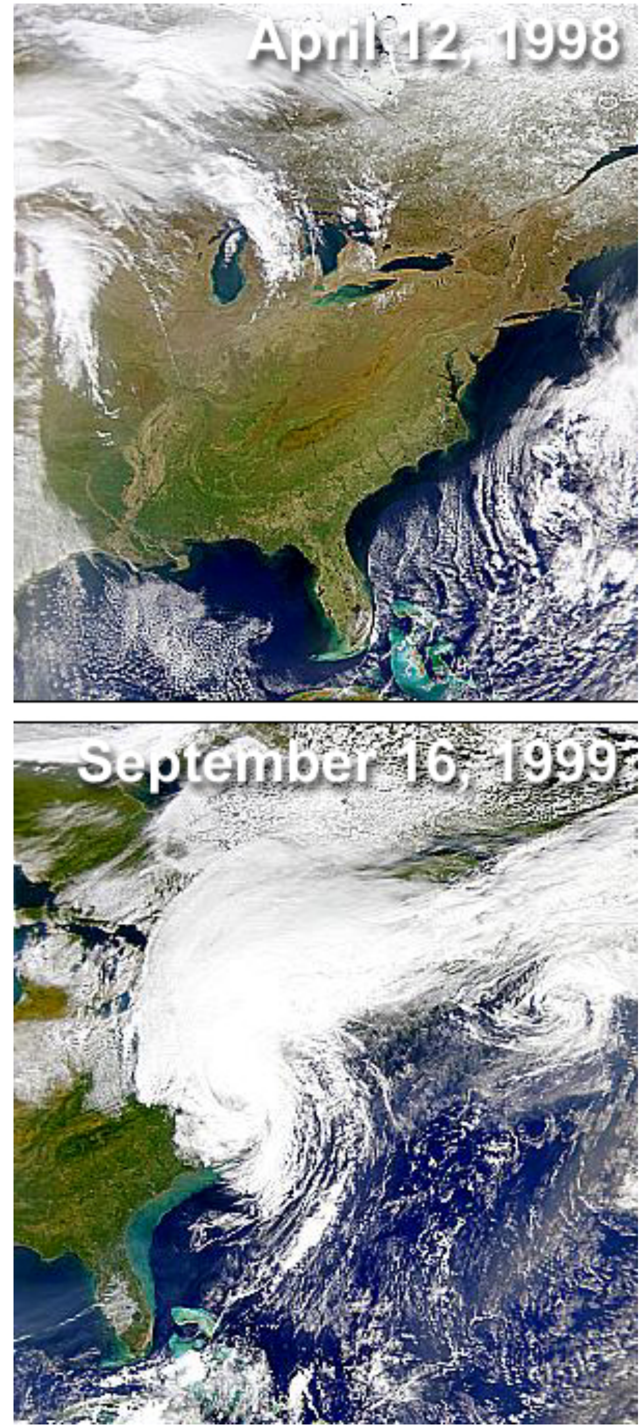
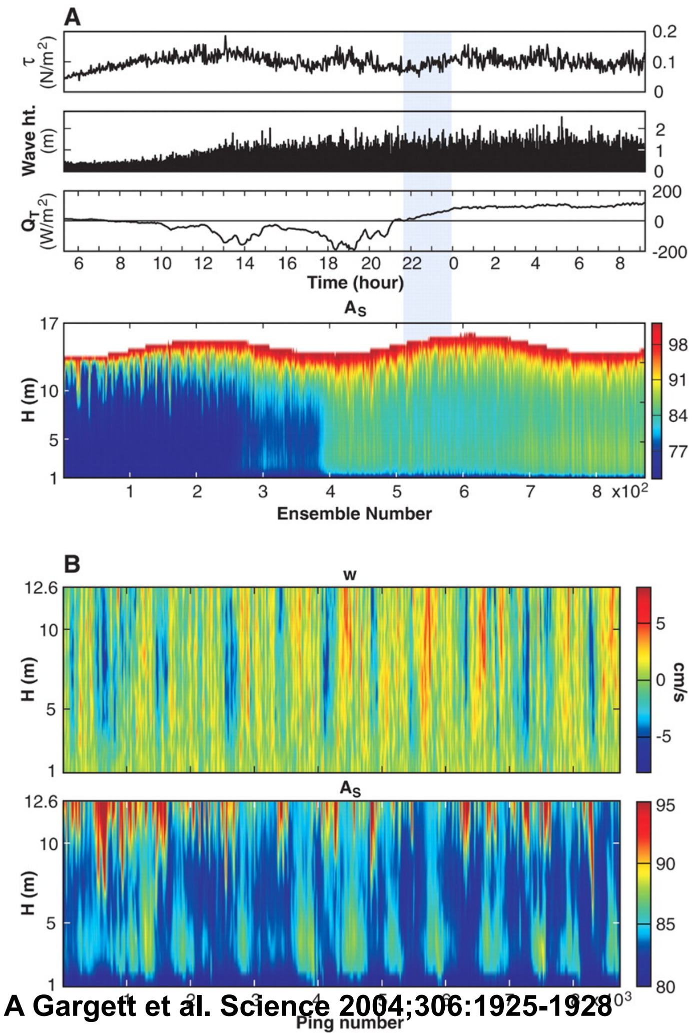


Fig. 1. (A) Atmospheric forcing (wind stress τ and net heat flux QT positive for ocean heat loss) and wave height spanning a period of increase in water column backscatter As on 16 May 2003.

Langmuir circulation affects resuspension.



A Gargett et al. Science 2004;306:1925-1928

Published by AAAS

Now for some animations seeing all the processes region by region

- Thanks to Gene Feldman NASA

Gulf of Alaska

- Surface Salinity
- Note
  - Coastal Currents
  - Offshore jets and eddies
  - Flow through into Bering

West Coast

- Upwelling center
- Offshore jets and eddies
- River plumes
- ENSO events
- Coastal trapped waves

Gulf of Mexico

- Loop Current –Loop Current cycles
- Frontal Eddies
- Detached eddies
- Wide shelves

NE

- Coastal currents
- Slope Current
- Gulf Stream
- Labrador Current
- Cold Pools

SE Coast

- Frontal eddies
- Meandering
- Charleston Bump
- Next look subsurface

End

- Thanks.
- I look forward to the coming talks and the breakouts.

Regions of Freshwater Influence (ROFIs)

- Strong gradients
- Variable stratification
- Variable shading

Sources, transport and sinks within shelf seas

Onshore

- Nearshore – wave bottom interaction increase mixing *
- Regions of freshwater influence (ROFI's) increase stratification and have nutrient input.
- Well mixing throughout year - tide and wind
- Tidal mixing fronts
- Thermally stratified
- Shelf edge fronts, internal waves *

* = always present

Offshore

- From Gene
- here are links to a couple of very cool animations and should get you started:
- try the various mpeg options for the animation. not sure which works best on your system:
- global and north atlantic:
- http://svs.gsfc.nasa.gov/vis/a000000/a003400/a003468/index.html
- global and north pacific:
- http://svs.gsfc.nasa.gov/vis/a000000/a003400/a003471/index.html
- gulf of mexico:
- http://svs.gsfc.nasa.gov/vis/a000000/a003500/a003518/index.html
- west coast:
- http://svs.gsfc.nasa.gov/vis/a000000/a003500/a003517/index.html
- northeast:
- http://svs.gsfc.nasa.gov/vis/a000000/a003500/a003515/index.html
- sea surface temperature:
- http://svs.gsfc.nasa.gov/vis/a000000/a003300/a003388/index.html
- regards,
- gene

Mixing Processes – the stratification parameter

$$\varphi = \frac{1}{h}\int_{-h}^{0}(\bar{\rho} - \rho)gz\,dz$$

What controls stratification? They are quantifiable.

$$\frac{\partial \varphi}{\partial t_{w,h,e,c}} = -\delta K_s \rho_a \left(\frac{W^3}{h} \right) + \frac{\alpha g Q}{2 c_p} + \frac{1}{320} \frac{g^2 h^4}{N_z \rho} \left(\frac{\partial \rho}{\partial x} \right)^2 - \varepsilon K \rho_w \left(\frac{\overline{u}^3}{h} \right)$$

Time change in stratification

Wave Mixing

Heating Cooling

Estuarine Circulation

Tidal Mixing

Runoff/Evap/Precip and Advection

Lund-Hansen et al 1996

Successive regions offshore - Nearshore

- Turbulence, mixing, sediment resuspension, light attenuation.
- Emphasizes benthic regeneration, nutrients from ground water
- Figure shows resuspension during wind event off west Florida. Nutrient concentrations increased.
- These may lead to HAB's.

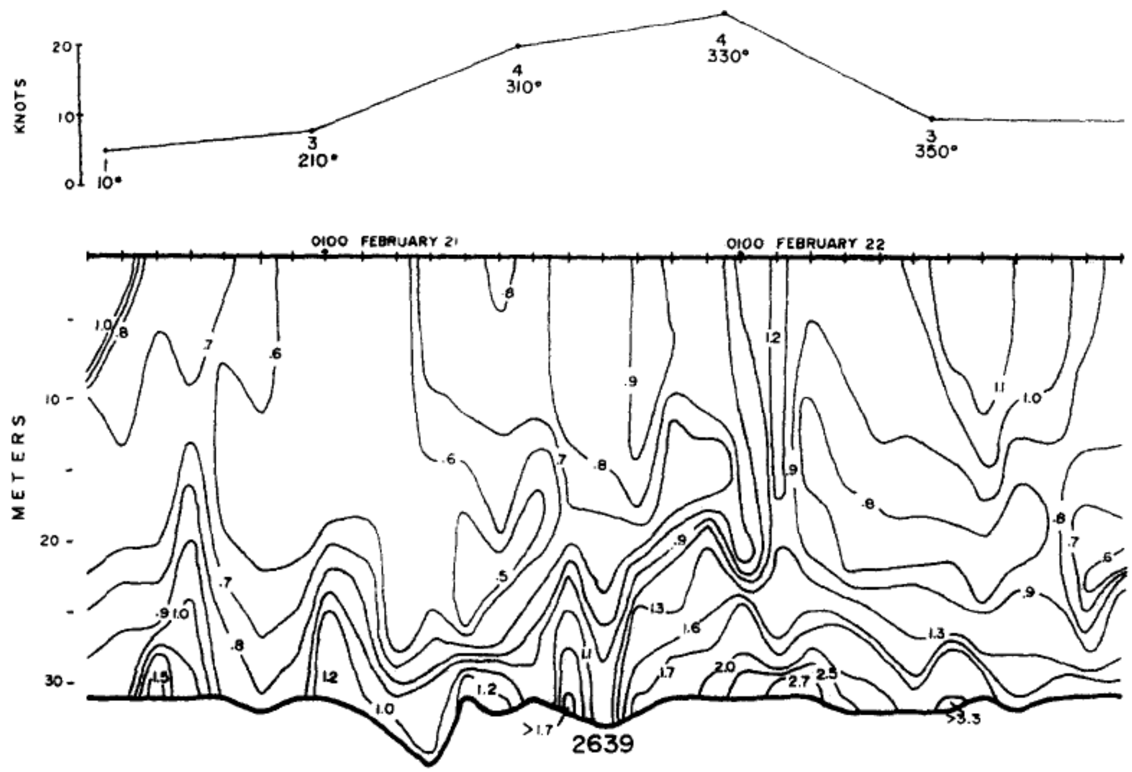


Fig. 2. Variation in physical parameters during passage of a 1978 winter storm front at Sta. 2639, SSE of Mobile Bay (29°53′N, 88°12′W). Top: wind speed, wind direction, sea state. Bottom: vertical profile of beam attenuation coefficient of the transmissometer (c_p) (m^{-1}).

Fanning, Carder and Betzer 1982

Coastal trapped waves – affect existing processes in time and space

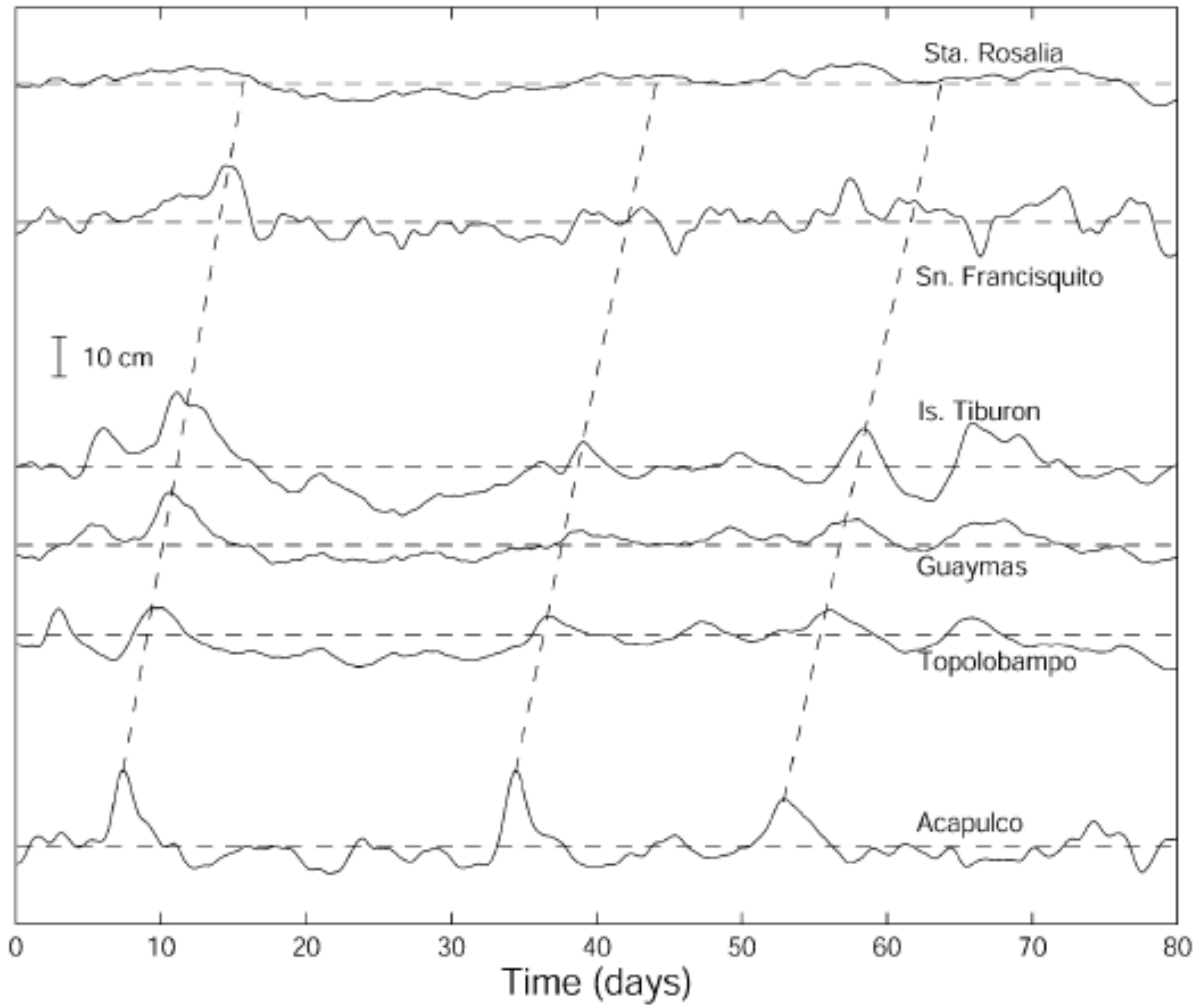


FIG. 5. Observed sea level at six stations along the coast (Fig. 1). The separation between the curves is proportional to their along-coast distance. The dashed lines show propagation of some of the larger disturbances at a speed around 3 m s^{-1}. Day 0 corresponds to 5 Jul 1984.

What can disrupt the normal along isobath flow that may bring nutrients onshore?

- Processes specific to or enhanced at the shelf edge.
- Relaxation of the geostrophic constraint near the equator (Coriolis term goes to zero).
- Friction as occurs in Ekman layers.
- Non-conservative processes. The net flux <uC> may be non-negative along some boundary as C may vary due to phytoplankton uptake of nitrogen for example.
- Small scale (time O(1 day), length O(2 - 10 km), speed O(0.2 - 1 m/s)) local, non-linear and time dependent flows tend towards ageostrophic.

Huthnance 1995